

# Regulatory Implications of Using Constructed Wetlands to Treat Selenium-Laden Wastewater

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The practice of using constructed wetlands to treat selenium-laden wastewater is gaining popularity in the United States and elsewhere. However, proponents of treatment wetlands often overlook important ecological liabilities and regulatory implications when developing new methods and applications. Their research studies typically seek to answer a basic performance question—are treatment wetlands effective in improving water quality—rather than answering an implicit safety question—are they hazardous to wildlife. Nevertheless, wetland owners are responsible for both the operational performance of treatment wetlands and the health of animals that use them. This is true even if wetlands were not created with the intent of providing wildlife habitat; the owner is still legally responsible for toxic hazards. If poisoning of fish and wildlife occurs, the owner can be prosecuted under a variety of federal and state laws, for example, the Migratory Bird Treaty Act and the Endangered Species Act. In considering this type of treatment technology it is important to document the selenium content of the wastewater, understand how it cycles and accumulates in the environment, and evaluate the threat it may pose to fish and wildlife before deciding whether or not to proceed with construction. Many of the potential hazards may not be obvious to project planners, particularly if there is no expressed intention for the wetland to provide wildlife habitat. Ecological risk assessment provides an approach to characterizing proposed treatment wetlands with respect to wildlife use, selenium contamination, and possible biological impacts. Proper application of this approach can reveal potential problems and the associated liabilities, and form the basis for selection of an environmentally sound treatment option. © 2002 Elsevier Science (USA)

## INTRODUCTION

There has been a major expansion in the use of constructed wetlands for treating industrial, municipal,

and agricultural wastewater during the past two decades. Textbooks such as those by Hammer (1989), Moshiri (1993), and Kadlec and Knight (1996) attest to the escalation in awareness and application of this treatment technology. Constructed wetlands can substantially improve down-gradient water quality by removing pollutants through a variety of chemical, physical, and biological processes. Pilot or operational-scale wetlands have been used to remove everything from sediment and nutrients to organic chemicals, pesticides, trace elements, and heavy metals. With their apparent low cost relative to conventional wastewater treatment methods, as well as the environmentally friendly image they generally convey, constructed wetlands have become popular throughout many regions of the world (Kadlec and Knight, 1996).

In addition to improving water quality, treatment wetlands create habitat for wildlife—sometimes conspicuous, sometimes not. In some cases the habitat function may be considered a valuable feature, and it may even influence the construction design of wetlands to enhance wildlife use; in others it may be overlooked or ignored. Whether recognized or not, it is important to understand that the habitat feature will attract wildlife, which may be exposed to hazardous concentrations of pollutants retained in the wetlands (e.g., Helfield and Diamond, 1997). Poisoning of wildlife is especially likely when wastewater contains a substance that bioaccumulates in their food organisms, for example, selenium (Ohlendorf *et al.*, 1986a,b; Lemly *et al.*, 1993; Skorupa, 1998). Thus, it is possible for treatment wetlands to create toxic conditions while at the same time improving water quality for down-gradient ecosystems.

The overlap of these two factors, contaminant removal and wildlife exposure, conveys important responsibilities to wetland owners and managers. They are responsible for both the operational performance of treatment wetlands and the health of animals that use them. This is true even if

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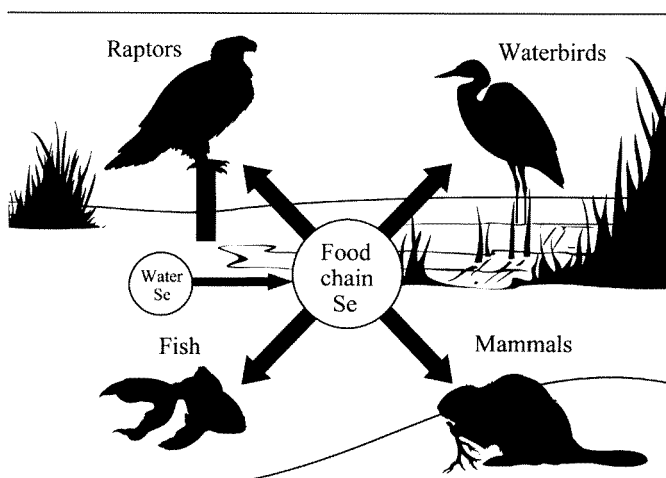
wetlands were not created with the intent of providing wildlife habitat; the owner is still legally responsible for toxic hazards. For example, if poisoning of migratory waterfowl or shorebirds occurs, the owner can be prosecuted for violating the Migratory Bird Treaty Act (Margolin, 1979). Proponents of treatment wetlands often overlook this type of liability when developing new methods and applications (e.g., Rodgers and Dunn, 1992; Hawkins *et al.*, 1997; Hansen *et al.*, 1998; Terry and Zayed, 1998). Their research studies typically seek to answer a basic performance question—are treatment wetlands effective in removing contaminants?—rather than answering the implicit safety question—are they hazardous to wildlife?

In this article we examine the selenium liability issue by discussing a classic case example that illustrates where and how problem situations can arise, and the possible regulatory consequences to wetland owners. We also provide guidance on how ecological risk assessment can be used to evaluate proposed treatment wetlands and identify problems.

#### ECOLOGICAL LIABILITY: CREATING TOXIC HAZARDS TO WILDLIFE

The major objective of treatment wetlands is to remove materials that could threaten the health and biological integrity of down-gradient receiving waters. If that goal is achieved, ecological benefits result. However, if the wastewater being treated contains selenium, the apparent benefits to down-gradient water quality can be more than offset by toxic hazards created within the wetlands. The end result can be a net loss of benefits and creation of an ecological liability that would not exist if predischARGE wastewater treatment technologies were used. Treatment wetlands may thus raise serious environmental safety issues.

There are two principal factors responsible for ecological liability. First is that selenium strongly bioaccumulates in wetland plants and animals. Bioaccumulation creates an important dichotomy; on one hand, it can remove selenium from water and make wetlands very effective treatment tools; on the other hand, it can render wetlands unsafe by exposing wildlife to toxic levels of selenium (Fig. 1). For example, waterborne selenium concentrations of 2–16  $\mu\text{g Se/L}$  (parts per billion) can increase manyfold in aquatic food chains and may reach 35,000 times the water concentration in fish and wildlife tissues (Lemly, 1993a), resulting in damage to internal organs, physiological dysfunction, and death (Sorensen, 1986; Ohlendorf *et al.*, 1988a). In addition to these direct toxic effects, there are also important indirect impacts. Selenium consumed in the diet of adult birds and fish is passed to their offspring in eggs, where embryos absorb the selenium as they develop.



**FIG. 1.** Major pathways for selenium movement in wetland ecosystems. The same process that makes treatment wetlands effective in removing selenium from water—bioaccumulation in food chains—can render them unsafe by exposing wildlife to toxic levels of selenium in their diet. Those who are considering treatment wetlands for selenium removal need to understand the ecological liabilities associated with this technology as well as the regulatory implications that can result if wildlife poisoning occurs.

The consequences can be severe, culminating in teratogenic deformities, reproductive failure, and elimination of entire animal communities (Ohlendorf *et al.*, 1986a; Hoffman *et al.*, 1988; Lemly, 1985a,b, 1993b). Waterborne concentrations above 16  $\mu\text{g Se/L}$  pose an even greater threat to wildlife health (Ohlendorf, 1989; Ohlendorf *et al.*, 1986b; Skorupa and Ohlendorf, 1991; Lemly, 1997a). Wastewaters that are treated to remove selenium typically contain > 20  $\mu\text{g Se/L}$  (Hansen *et al.*, 1998) and thus fall into the highest risk category.

The habitat feature of constructed wetlands is the second principal factor in the liability scenario. It is important to understand that constructing wetlands—whether a 0.1-ha treatment cell or a 50-ha marsh—creates habitats suited to a variety of animals, particularly invertebrates eaten by fish and wildlife. This sets the stage for problems because a contaminant exposure pathway is established. Biologically removing selenium from water and providing wildlife habitat are not compatible wetland functions. However, it is not easy to separate the two and simply design a wetland to exclude wildlife. What might seem to be unattractive conditions from an engineering standpoint, e.g., shallow, hot, hypersaline water, no macrophytes or emergent vegetation, can turn out to be a magnet for wildlife because of invertebrates that flourish under those conditions (e.g., Parker and Knight, 1989). Short of enclosing wetlands under domes, there is no method that will completely eliminate wildlife exposure to selenium contamination. For example, perimeter fences may exclude certain mammals but do not affect use by birds (Hawkins

*et al.*, 1997). Propane noise cannons and human patrols may not eliminate poisoning of waterfowl and shorebirds (Zahm, 1986; Hoffman *et al.*, 1986). Even covering a wetland with screening to exclude birds still allows passage of selenium-contaminated insects, which can be a significant route of exposure for insectivorous birds and mammals (Hothem and Ohlendorf, 1989; King *et al.*, 1994). Taking the steps necessary to reduce ecological liability can increase the cost of wetland treatment dramatically, perhaps to the point of making the project unfeasible from an economic standpoint.

The most insidious reason for liability problems is the failure of those who develop wetland selenium treatments to adequately evaluate risks to wildlife. Because of highly publicized examples of selenium-poisoned waterfowl and shorebirds (e.g., Kesterson Marsh, CA; see following case example), the need to thoroughly examine these risks should be obvious, yet major oversights continue to occur. For example, researchers developing treatment methods typically seek to establish how effective wetlands can be in removing selenium from water, but make little effort to document or disclose ecological liabilities. This is particularly evident with regard to "phytoremediation" techniques that rely on bioaccumulation as the selenium removal mechanism (e.g., Hansen *et al.*, 1998; Terry and Zayed, 1998). Consequently, the methods have inherent dangers that are not readily apparent to potential users. Another major source of problems is failure to recognize that selenium should be a high priority concern in the wastewater being treated. For example, methods developed to remove heavy metals (Cu, Pb, Zn) from oil refinery effluents (e.g., Hawken *et al.*, 1997) do not recognize the presence of elevated selenium ( $>20 \mu\text{g Se/L}$ ) in the wastewater or acknowledge the potential for creating environmental hazards. Moreover, selenium is not mentioned as an item of concern when refinery effluents are discussed in treatment technology textbooks (e.g., Kadlec and Knight, 1996), or when case examples are used to illustrate the benefits of wetland treatment of refinery wastewater (e.g., Amoco Oil Company's Mandan, North Dakota Refinery; Hammer, 1989; Kadlec and Knight, 1996). Similar problems exist in recognizing potential threats from coal processing materials and combustion wastes (e.g., Hammer, 1989; Kadlec and Knight, 1996), all of which can contain high concentrations of selenium and lead to significant environmental hazards (Lemly, 1985b). These oversights are a major shortcoming that is pervasive in the wetland treatment technology field. It is essential to know the entire chemical matrix of wastewater and evaluate each component under the planned treatment scenario.

Many wetland treatment methods are being marketed without full knowledge or disclosure of the risks they pose to wildlife. Those who wish to apply the methods should

have a clear understanding of the ecological liabilities that can result.

#### REGULATORY IMPLICATIONS: FEDERAL AND STATE STATUTES

In the United States, legal responsibility for endangering the health of wildlife stems from a variety of federal and state laws. At the federal level, liability is imposed primarily by the Migratory Bird Treaty Act and the Endangered Species Act. State environmental laws may augment these statutes to create significant additional liability at a local level. For example, in California the Toxic Pits Act, the Katz Act, the Porter-Cologne Water Quality Control Act, and the Public Trust Doctrine all frame the definition of environmental acceptability in which treatment wetlands must function (Dunning, 1985). Thus, it is critical for those who wish to construct treatment wetlands to understand the laws that will determine the ultimate fate of their projects. Because of broad applicability and implications, the principal federal statutes are discussed here in some detail.

##### *Migratory Bird Treaty Act (MBTA)*

This statute was legislated by Congress in 1918 to implement the convention between the United States and Great Britain protecting certain birds that migrate between the United States and Canada. Migratory bird treaties were later reached with Mexico, Japan, and Russia, and the Act was amended in 1974 to bring these treaties within its provisions (Margolin, 1979; Vencil, 1986). For many years, criminal prosecutions under the Act were for violations of hunting regulations. Then in 1978 there were two cases that extended prosecutions and convictions to situations where birds were not intentional targets. Those cases involved inadvertent deaths of birds resulting from pesticide contamination. In the first case, poisoning occurred as a result of wastewater released from a pesticide manufacturing process. The U.S. Court of Appeals for the Second Circuit held that intent to kill birds is not required for conviction under the MBTA. In the second case, birds died in a field recently sprayed with an insecticide. The District Court of the United States for the Eastern District of California reached the same decision with regard to criminal liability. These two court decisions set an important precedent that has far-reaching implications for treatment wetlands. The MBTA provides a means of prosecuting those who bring harm to birds, regardless of intent (Margolin, 1979). This liability cannot be eluded by saying that treatment wetlands were not created to provide habitat for wildlife. If poisoning occurs, the owners/operators are in violation of the MBTA. Importantly, many of the birds likely to be attracted to treatment

wetlands fall under MBTA protection: waterfowl, shorebirds, and a variety of wading birds.

The penalties imposed under the MBTA are substantial, and suits can be brought by private citizens, conservation groups, natural resource management agencies, and regulatory authorities (Vencil, 1986). Killing one bird constitutes a violation and conviction carries a fine of \$US 500.00 and 6 months imprisonment, or both, on each count. The prosecution can charge counts for each type of bird poisoned and each day on which birds are killed (Vencil, 1986). Thus, the greater the degree and persistence of impacts to wildlife health, the greater the potential penalty. For example, a poisoning event that kills three kinds of birds on 6 consecutive days could generate 18 counts, with a total fine of \$US 9000.00 and a jail term of 9 years.

The power of the MBTA is evidenced by the outcome of major state and federal cases in which it was not even invoked in a court proceeding, but only raised as an issue. For example, the U.S. Department of the Interior (DOI) constructed Kesterson Marsh for wildlife habitat during the 1970s). In the 1980s, selenium-laden drainage from DOI-managed agricultural irrigation projects entered the marsh and caused deaths of waterfowl and shorebirds (see following case example on Kesterson Marsh). Advised of liability under the MBTA, then Secretary of the Interior Donald Hodel ordered Kesterson closed to the public, changed water management practices to stop inflow of irrigation drainage, and implemented an elaborate hazing program to scare birds away (Popkin, 1986; Zahm, 1986). However, hazing was not completely effective and some bird poisoning—and liability—continued. Kesterson Marsh was eventually removed from the National Refuge System, drained and capped with uncontaminated soil, and managed by DOI as an upland site.

Kesterson Marsh was a large (518 ha) wetland designed to serve two purposes: treat (store and evaporate) irrigation drainage and provide wildlife habitat. These were not compatible functions. However, it does not take a Kesterson with its massive poisoning of wildlife for legal problems to occur. Treatment wetlands need not be hundreds of hectares in size or intentionally provide habitat to incur liability. Whatever size, shape, or primary function, treatment wetlands are all subject to the same wildlife safety responsibilities conveyed by the MBTA.

### *Endangered Species Act (ESA)*

In contrast to MBTA, the federal endangered species program has a relatively recent origin. Congressional legislation implementing the ESA dates only to 1973. Two elements of the statute that have particular relevance for constructed wetlands are: (1) to protect against killing (intentional or unintentional) of listed endangered and

threatened species, and (2) to prevent degradation of habitat that supports those species. Creating a treatment wetland whose contaminant load poisons wildlife or plants violates both of these elements.

The current federal list includes 896 endangered species (343 animals, 553 plants) and 230 threatened species (115 animals, 115 plants) (U.S. Fish and Wildlife Service, 1998). Although what constitutes a count and violation under ESA is similar to that under MBTA, penalties under ESA are more severe. For example, each count can carry a fine exceeding \$US 10,000.00 and 1 year imprisonment, or both. An important point to note is that there are numerous state laws that complement and extend the federal legal authority for ESA to a local level. Many states also have their own lists of endangered and threatened species, which makes liability under ESA even more broad and far reaching (Bean, 1986).

It is not necessary for an endangered or threatened species to live exclusively within a treatment wetland for it to be protected under ESA. If a species uses the habitat in any way (resting, migration stopover, etc.), it is fully covered. This is especially important because the new habitat provided by constructed wetlands may attract wildlife from their native range on a seasonal basis or for a specific purpose, e.g., feeding. Once endangered wildlife or plants colonize or use the constructed wetland, liability for their well-being conveys to the owner/manager. Of particular interest is the potential for situations in which the wildlife species of concern do not use the wetland site directly, but feed on small rodents or other animals that move off-site and carry their body burden of contaminants with them, for example, predatory birds and mammals.

At first glance, the likelihood of having endangered or threatened species in a treatment wetland may seem remote. However, as the list of species grows, both at the federal and state levels, so does the potential for interaction with constructed wetlands. This is particularly true in arid and semiarid regions where wetland habitat is very scarce. Moreover, water utilization policies have compounded the problem in many locations. For example, since the late 1800s, Western U.S. water law has provided for agricultural uses at the expense of in-stream flow and wetland preservation. The steady shrinking of wetland habitat has reached a critical point for many species, including several that are endangered and threatened. Constructed wetlands are a virtual oasis for wildlife in those situations (Lemly *et al.*, 1993) and it is not unrealistic to expect that sooner or later the ESA will come into play.

As with MBTA, it is important to understand that creating treatment wetlands also creates liability for wildlife exposure to contaminants. Endangered and threatened animals and plants are an important consideration within that exposure scenario. The legal implications

should be recognized and used to guide decisions during the planning phase of wetland construction projects.

### CASE EXAMPLE: KESTERSON MARSH

#### Background

The Kesterson Marsh episode has become a classic case for illustrating the dangers of selenium in treatment wetlands. That episode came about because of ambitious agricultural water management plans coupled with a failure to recognize selenium as an environmentally hazardous constituent in wastewater. The series of events that culminated in wildlife poisoning began in 1949, when the U.S. Bureau of Reclamation (USBR) submitted a status report to Congress recommending additional water development for the Central Valley Project (CVP) in California. The USBR also noted that because subsurface soils on the west side of the San Joaquin Valley consisted of impervious clay that prevented deep infiltration of water, continued intensive irrigation could lead to salt buildup that would reduce crop production unless drainage systems were installed to collect and convey return flows to the Sacramento–San Joaquin River Delta, San Francisco Bay, and the sea (Moore *et al.*, 1990). The first subsurface drainage systems were installed in the 1960s, concurrent with the construction of the San Luis Unit of the CVP (Beck, 1984). Irrigation drainwater was dealt with on a piecemeal basis until the late 1970s, when the San Joaquin Valley Interagency Drainage Program was formed to review drainage needs for the valley. That program recommended construction of a valleywide master drain with a series of flow-regulating reservoirs to be operated as wetlands for wildlife (SJVIDP, 1979).

The master San Luis Drain was originally designed to be operated in conjunction with adjacent regulating reservoirs to seasonally discharge subsurface irrigation wastewater into the river delta during periods of high outflow, thereby ensuring drainage water dilution. Kesterson Reservoir (a series of 12 shallow ponds collectively known as Kesterson Marsh) was the first regulating reservoir to be built (Moore *et al.*, 1990). In 1970, the U.S. Fish and Wildlife Service (USFWS) and the USBR signed a cooperative agreement for management of Kesterson Marsh and associated uplands. That agreement formally designated 2390 ha as Kesterson National Wildlife Refuge (NWR), and specified that the USFWS manage the area for wildlife and associated recreational values, but retained the right for USBR to use the marsh for management of irrigation drainwater (Zahm, 1986). By 1972, only 132 km of the intended 302 km of the master drain was finished, and project funds were depleted. The 518-ha Kesterson Marsh became the terminus of the drain, and its 12 shallow ponds functioned as a treatment wetland for evaporating agri-

cultural irrigation wastewater (Zahm, 1986; Moore *et al.*, 1990).

#### Accumulation of Selenium and Impacts to Wildlife

Through the mid-1970s the San Luis Drain conveyed a mixture of operational spillage from valley water projects, agricultural surface runoff, and subsurface drainage. In 1978 the proportion of subsurface drainwater increased, and by 1981 almost all of the flows discharged into Kesterson Marsh were composed of subsurface drainage generated by 3240 ha of irrigated agricultural lands in the Westlands Water District (WWD) of the San Luis Unit (Zahm, 1986). In 1980–1981, samples of water from the drain and Kesterson Marsh were found to be saline and contaminated by selenium (15–400 µg Se/L) (Saiki, 1986a). The source of selenium was later determined to be natural seleniferous soils in the WWD. Irrigation water dissolved and leached selenium out of the soil as it percolated downward, and carried it to Kesterson Marsh in the resultant subsurface drainage.

Beginning in 1982, biological surveys were conducted by the USFWS to determine the extent and severity of selenium contamination in aquatic food chains at Kesterson Marsh (Saiki, 1986a,b; Hothem and Ohlendorf, 1989; Schuler *et al.*, 1990). Extensive chemical analyses revealed that selenium concentrations were greatly elevated in the water, detritus, and food organisms present in the reservoir. Some of the highest concentrations of selenium ever reported for fish tissues (370 µg Se/g dry) were found in these early studies. Aquatic invertebrates and forage fish contained from 1000 to 5000 times the concentrations of selenium present in the water, which indicated that significant bioaccumulation was occurring. Elevated selenium concentrations were found in every animal group coming in contact with Kesterson Marsh, including fish, birds, insects, frogs, snakes, and small mammals (Saiki, 1986a; Clark, 1987; Ohlendorf *et al.*, 1988b, 1990). High selenium concentrations were also found in food organisms of predatory birds and endangered species such as the San Joaquin kit fox (*Vulpes macrotis mutica*).

Field studies indicated a high frequency (up to 65%) of selenium-induced developmental deformities in the embryos and hatchlings of waterfowl and other aquatic birds nesting at Kesterson Marsh (Ohlendorf *et al.*, 1986a, 1989; Williams *et al.*, 1989). Congenital malformations were often multiple and consisted of missing eyes and feet, protruding brains, and grossly deformed beaks, legs, and wings (Ohlendorf *et al.*, 1986b, 1988a; Hoffman *et al.*, 1988). Four species of ducks (mallard, *Anas platyrhynchos*; pintail, *A. acuta*; cinnamon teal, *A. cyanoptera*; gadwall, *A. strepera*), coot (*Fulica americana*), avocet (*Recurvirostra americana*), grebe (*Podiceps nigricollis*), and stilt (*Himantopus mexicanus*) were affected. Several

pathological and biochemical symptoms of selenium toxicosis were also found in the adult wild birds (Ohlendorf *et al.*, 1988a). Estimates indicated that several thousand birds were poisoned.

Other field studies documented a massive fish kill at Kesterson Marsh in 1983 (Saiki, 1986a), followed by a high frequency (30%) of selenium-induced stillbirths in mosquitofish (*Gambusia affinis*), the only fish species that managed to persist in the reservoir and the San Luis Drain (Saiki *et al.*, 1991, Saiki and Ogle, 1995).

#### *Consequences to the Wetland Owner*

By 1985, selenium-induced death and deformities had affected thousands of aquatic birds, and the "poisoned" refuge became highly publicized (Marshall, 1985; Popkin, 1986). Threats of lawsuits against the Department of the Interior, the federal agency with stewardship/ownership responsibility for Kesterson, were voiced by several environmental groups and private citizens. Soon after the toxic threat of contaminants in irrigation drainage was verified, then Secretary of the Interior Donald Hodel, citing concerns over violation of the Federal Migratory Bird Treaty Act, officially closed Kesterson National Wildlife Refuge to the public, began a hazing program to scare waterfowl and other wildlife away from the refuge, and issued an order for the San Luis Drain to be plugged (USGAO, 1987). By June 1986, all irrigation drainage flows into Kesterson Marsh had stopped. In 1987 USBR implemented a cleanup plan that called for drainage of the wetlands, excavation and on-site disposal of contaminated soil and plant material in a lined and capped containment area, and long-term site monitoring to detect possible off-site seepage of selenium-contaminated water. The cost of the cleanup was about \$US 50 million (1987 dollars) (USGAO, 1987; SJVDP, 1988). The lands constituting Kesterson Marsh were removed from the national refuge system and placed under the jurisdiction of USBR for management as a contaminated landfill. To offset this loss of wetlands, some 9500 ha of private lands adjoining the refuge was purchased and developed into waterfowl and upland wildlife habitat (USGAO, 1987; SJVDP, 1990). The total cost of mitigating selenium contamination at Kesterson was about \$US 60 million (1987 dollars), not including the ongoing cost of long-term site monitoring, which continues today.

#### *Implications for Treatment Wetlands*

The lessons learned at Kesterson were painful but valuable. First, it is essential to know the contaminants in wastewater and their hazards to wildlife; selenium surprised many of those involved with Kesterson but it need not have. Information available at the time was adequate to reveal the environmental safety issue sur-

rounding irrigation drainage. Second, using wetlands to treat agricultural irrigation drainage can set the stage for severe impacts to fish and wildlife. Bioaccumulation of selenium in aquatic food chains can lead to a variety of reproductive impacts as well as selenium toxicosis in adult animals. Third, if treatment wetlands are contaminated by selenium to the point that wildlife problems occur, aggressive cleanup will likely be necessary and it is extremely expensive. This may more than offset perceived or actual cost savings of the wetland treatment option when it was designed and implemented. Fourth, there are serious regulatory issues relating to the Migratory Bird Treaty Act and the Endangered Species Act that can come into play. Violation of these and other laws may impose severe penalties on the wetland owner.

#### **PREVENTING PROBLEMS THROUGH ECOLOGICAL RISK ASSESSMENT**

It is important for those considering wetlands as a selenium treatment method to understand the ecological risks. Many of the risks may not be obvious to project planners, particularly if there is no expressed intention for the wetland to provide wildlife habitat. Ecological risk assessment provides an approach for characterizing proposed treatment wetlands with respect to wildlife use, selenium contamination, and possible impacts. Proper application of this approach can reveal potential problems and the associated liabilities, and form the basis for selection of an environmentally sound treatment option. Although it is beyond the scope of this article to give an exhaustive detail of assessment procedures, a brief overview is presented as a foundation from which the reader can obtain additional information.

#### *Assessment Guidelines*

The USEPA (1992, 1998) has developed a "framework" to serve as guidance for conducting ecological risk assessments that are applicable to a wide range of potential ecological effects. The guidance is intended to provide a simple, flexible structure for conducting and evaluating ecological risks and to foster consistent approaches to ecological risk assessment. This structure includes three major steps called Problem Formulation, Analysis, and Risk Characterization (Fig. 2).

Some of the individual U.S. states as well as various other agencies also have developed guidance for conducting ecological risk assessments. Although these guidance documents vary in specifics and may apply only to a particular type of site or kind of facility, there are many common elements among them. Following the USEPA framework guidance should help ensure that an ecological risk assessment will address the important issues for a treatment wetland.

## FRAMEWORK FOR A WETLAND-SPECIFIC ECOLOGICAL RISK ASSESSMENT

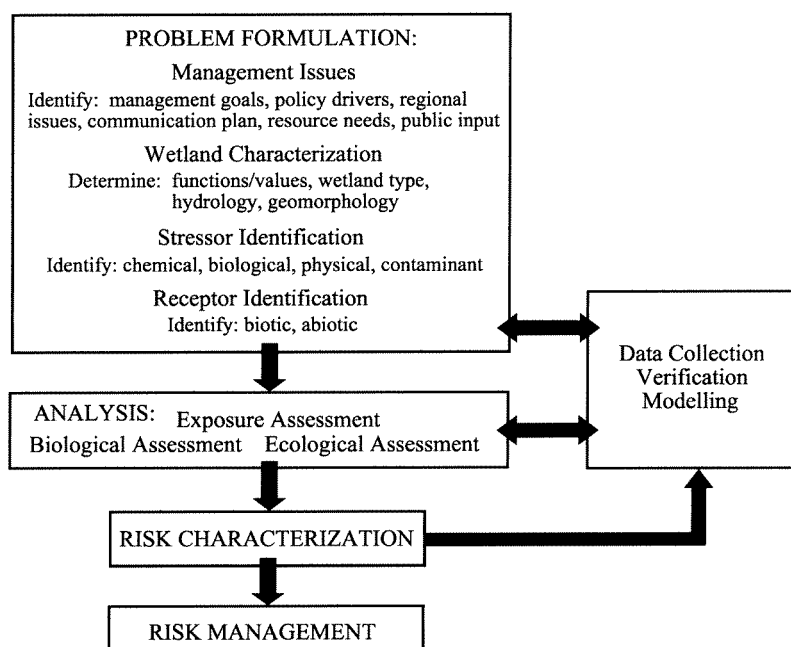


FIG. 2. Various steps and components of the risk assessment process for wetlands. (Adapted, with permission, from USEPA 1992).

The USEPA framework (1992, 1998) emphasizes the importance of discussion between the risk assessor and the risk manager (the person or persons who must decide how to manage the site), especially at two times (Fig. 2). Early discussions are important in ensuring that the risk assessment will focus on the questions about which the manager wants information, and that the manager understands the limitations concerning how much information the risk assessment is likely to produce. After the risk assessment is completed, discussions between the risk assessor and the risk manager help to interpret the findings and uncertainties related to them. The effectiveness of the risk assessment usually increases in proportion to the clarity of communication between the risk assessor and risk manager.

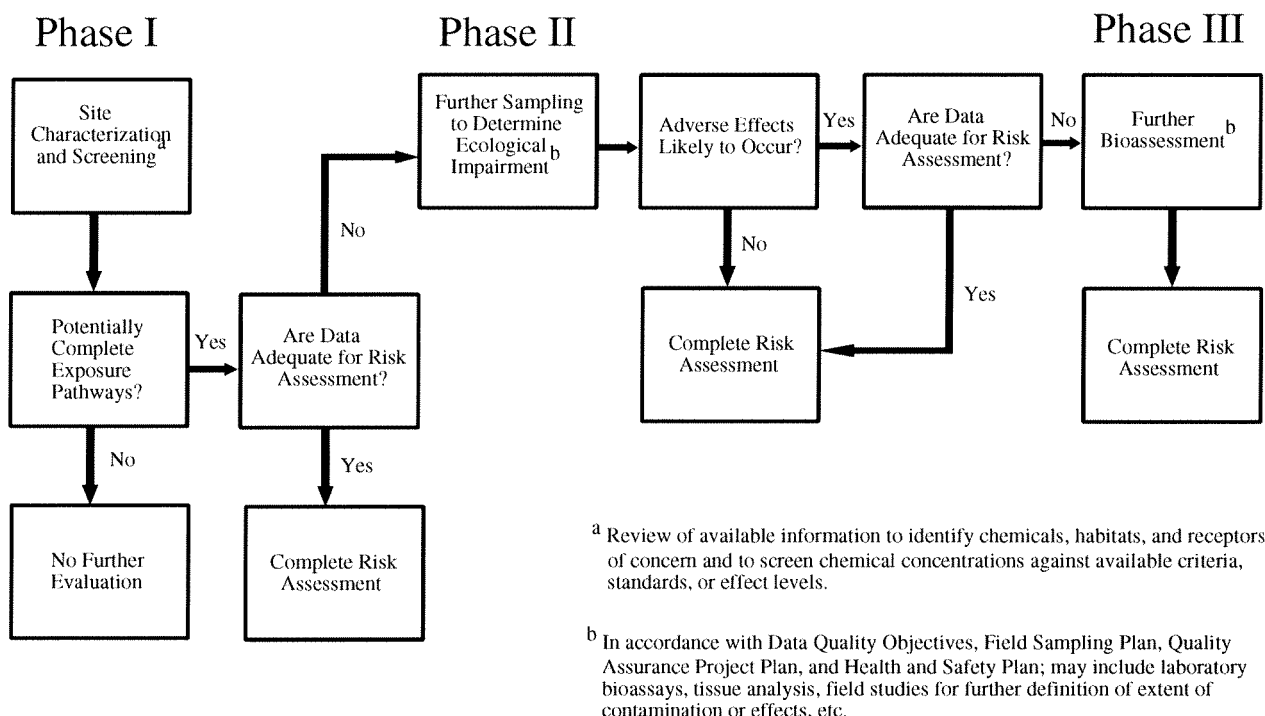
#### Ecological Objectives

The objectives of an ecological risk assessment are usually identified as "ecological endpoints" that are more or less subject to direct measurement. The overall objectives (called "Assessment Endpoints") are often not directly measurable, but are statements about the resources that are to be protected. Examples include: (a) protect waterfowl populations from chemicals that could bioaccumulate in the food chain, thereby potentially causing reproductive impacts in birds; or (b) maintain the integrity of a wetland food chain that provides habitat for aquatic birds. For each identified assessment endpoint,

there must be one or more parameters that can be measured and quantified. These have been referred to as "Measurement Endpoints," but the more recent USEPA guidance (USEPA, 1998) has changed that terminology to "Measures of Exposure," "Measures of Ecological Effects," and "Measures of . . ." For example, a measure of exposure for the first assessment endpoint listed above might be the concentration of selenium in food-chain organisms found in the wetland; a measure of ecological effects could be the hatching success of aquatic birds nesting at the wetland. For the second assessment endpoint, a measure of exposure might be the waterborne concentrations of all potentially toxic chemicals in the wetland.

#### General Organization and Content

The risk assessment report is usually organized to provide information concerning problem formulation, exposure assessment, ecological effect assessment, and risk characterization so it is consistent with the main activities that are conducted in the assessment. Figure 2 provides a schematic representation of the kinds of information that are typically included in each major section. However, because of space limitations, the specifics are not described here in detail. Readers are referred to the USEPA framework (USEPA, 1992, 1998) or similar documents for further explanation.



NOTE: Areas of concern, chemicals, exposure pathways, and receptors are evaluated independently so that further evaluation is only to satisfy identified needs.

FIG. 3. Typical phased approach to ecological risk assessment.

### Phased Approach

An important aspect of the approach to ecological risk assessment is not to do only the necessary work, but to do all of the work that is necessary (USEPA, 1992). This is accomplished by conducting the work in a phased manner, whereby the work completed in one phase helps to determine whether further studies are required and, if so, specifically what additional information is needed. Figure 3 shows this method of phasing the risk assessment for a wetland. Phase I is primarily the Problem Formulation, but it includes some preliminary evaluation of exposure and ecological effects. Phase II would be conducted in accordance with a sampling and analysis plan developed after Phase I has been completed. If further data needs are identified after Phase II is completed, additional studies may be conducted as Phase III.

The Phase I site characterization would review available information to:

- Identify chemicals in water or soils at the proposed site
- Describe habitats present or expected to develop in the wetland
- Identify receptors of concern (such as aquatic birds, fish, fish-eating mammals, etc.)

The chemical screening during this phase is conducted to:

- Compare chemical concentrations with established criteria or standards and with ecological effect levels (if criteria/standards have not been established)
- Evaluate potential bioaccumulation (especially for selenium and other persistent, bioaccumulative chemicals)

Phase I is a critical point in the evaluation of proposed treatment wetlands because it will likely be the step at which a decision is reached on whether to proceed with construction. The risk assessor must formulate a prediction of future conditions based on current information from the site concerning selenium concentrations and wildlife use. Phase I may be all that is possible (or necessary) before planners make a judgment on whether it is worthwhile, from a risk perspective, to pursue the project further. In situations when existing treatment wetlands are being evaluated, all three phases of risk assessment may be needed to assess risk under actual operating conditions.

When the Phase I site characterization and chemical screening have been completed, the question becomes "Is more information needed to complete the risk assessment?" There may be a generally inadequate amount of information, or it may be limited to a particular exposure pathway

or medium (such as selenium concentration in bird eggs). Some risk analysis protocols for selenium require information on several environmental matrices (e.g., water, sediment, benthic macroinvertebrates, fish, birds). If the answer to the question is "Yes," the next step is to develop the study plan (or sampling and analysis plan) for obtaining the additional information.

Typical objectives for a study plan include:

- Further characterization for wildlife use
- Determination of the exposure point chemical concentrations (including food-chain bioaccumulation)
- Evaluation of specific direct or indirect effects of chemical exposure under site-specific conditions

The plan should include the data quality objectives (such as required sample sizes, detection limits for chemical analyses, etc.) and the decision strategy/rationale that includes:

- Sample locations and methods
- Chemical analyses
- Bioassays and bioaccumulation assessment
- *In situ* biological effects assessment

For selenium, measurement of bioaccumulation in the food chain is particularly important when the receptors of concern are fish or aquatic birds. Chemical analyses of the water or sediment may be useful for evaluating exposure, but extrapolation to effects in fish or birds are predictive rather than proven. This issue has been discussed elsewhere (e.g., Skorupa and Ohlendorf, 1991) and is not repeated here.

The most important point about following this phased approach is that studies are conducted to satisfy specific information needs, and that the investigation can end as soon as those needs are met. This avoids the potential for the project becoming one of "open-ended research" that continues to follow up on leads that may be of interest to the investigator but will not provide information that the risk manager needs for decision-making purposes. However, in some instances the Phase II or III studies are essential for providing the needed information.

#### *Risk Characterization*

Once data and information collection efforts are completed, it is necessary to interpret the findings in the context of risks to fish and wildlife. Depending on the type of treatment wetland (proposed or existing) and specific needs of the assessment, this step may occur following Phase I, Phase II, or Phase III. Some of the primary indicators that can be used to determine risk include:

- Selenium concentrations exceeding hazard thresholds (water criteria or biological effects levels for diet/tissue)

- Mortality or reproductive impairment documented through *in situ* effects studies
- Teratogenic deformities found in combination with elevated tissue residues of selenium

There are several research reports and guidance documents available for interpreting selenium concentrations and biological effects and evaluating risks to fish and wildlife. The reader is directed to the following publications for more information: Hoffman *et al.* (1988), Lemly (1993a,b, 1995, 1996, 1997b), Ohlendorf (1989), Ohlendorf *et al.* (1986a, b, 1988a, 1989, 1990), Skorupa and Ohlendorf (1991), Skorupa *et al.* (1996), NIWQP (1998).

### CONCLUSIONS

The practice of using constructed wetlands to treat selenium-laden wastewater is gaining popularity in the United States and elsewhere. In considering this type of treatment technology it is important to document the selenium concentration of the wastewater, understand how it cycles and accumulates in the environment, and evaluate the threat it may pose to fish and wildlife before deciding whether to proceed with construction. It is also important to remember that constructing wetlands, even small ones, creates wildlife habitat and may lead to an exposure scenario that has strict regulatory penalties under various federal and state laws. Evaluating potential effects in wildlife should be an integral part of the planning stage for treatment wetlands. Ecological risk assessment provides a good framework for such evaluations, and the phased approach allows an assessment to address site-specific needs. For selenium, it is essential to evaluate bioaccumulation in the food chain to accurately assess risk. With this information in hand, environmentally sound choices for wastewater treatment can be made.

### REFERENCES

- Bean, M. J. (1986). The endangered species program. In *Audubon Wildlife Report 1986* (R. L. Di Silvestro, Ed.), pp. 347-371. Natl. Audubon Soc., New York.
- Beck, L. A. (1984). Case history: San Joaquin Valley. *Calif. Agric.* **38**, 16-17.
- Clark, D. R., Jr. (1987). Selenium accumulation in mammals exposed to contaminated California irrigation drainwater. *Sci. Total Environ.* **66**, 147-168.
- Dunning, H. C. (1985). Legal aspects of the Kesterson problem. In *Selenium and Agricultural Drainage: Implications for San Francisco Bay and the California Environment*. Pp. 118-129. Bay Institute of San Francisco, Tiburon, CA.
- Hammer, D. A. (1989). *Constructed Wetlands for Wastewater Treatment: Municipal, Industrial, and Agricultural*. Lewis, Chelsea, MI.
- Hansen, D., Duda, P. J., Zayed, A., and Terry, N. (1998). Selenium removal by constructed wetlands: Role of biological volatilization. *Environ. Sci. Technol.* **32**, 591-597.

- Hawkins, W. B., Rodgers, J. H., Jr., Gillespie, W. B., Jr., Dunn, A. W., Dorn, P. B., and Cano, M. L. (1997). Design and construction of wetlands for aqueous transfers and transformations of selected metals. *Ecotoxicol. Environ. Saf.* **36**, 238–248.
- Helfield, J. M., and Diamond, M. L. (1997). Use of constructed wetlands for urban stream restoration: A critical analysis. *Environ. Manage.* **21**, 329–341.
- Hoffman, S. E., Williams, N. J., and Herson, A. I. (1986). The Kesterson story. In *Proceedings of the First Biennial Conference: Is Current Technology the Answer?* pp. 1–9. Natl. Water Supply Improvement Associ. Springfield, VA.
- Hoffman, D. J., Ohlendorf, H. M., and Aldrich, T. W. (1988). Selenium teratogenesis in natural populations of aquatic birds in central California. *Arch. Environ. Contam. Toxicol.* **17**, 519–525.
- Hothem, R. L., and Ohlendorf, H. M. (1989). Contaminants in foods of aquatic birds at Kesterson Reservoir, California, 1985. *Arch. Environ. Contam. Toxicol.* **18**, 773–786.
- Kadlec, R. H., and Knight, R. L. (1996). *Treatment Wetlands*. CRC Press, Boca Raton, FL.
- King, K. A., Custer, T. W., and Weaver, D. A. (1994). Reproductive success of barn swallows nesting near a selenium-contaminated lake in eastern Texas, USA. *Environ. Pollut.* **84**, 53–58.
- Lemly, A. D. (1985a). Toxicology of selenium in a freshwater reservoir: Implications for environmental hazard evaluation and safety. *Ecotoxicol. Environ. Saf.* **10**, 314–338.
- Lemly, A. D. (1985b). Ecological basis for regulating aquatic emissions from the power industry: The case with selenium. *Regul. Toxicol. Pharmacol.* **5**, 465–486.
- Lemly, A. D. (1993a). Guidelines for evaluating selenium data from aquatic monitoring and assessment studies. *Environ. Monitor. Assess.* **28**, 83–100.
- Lemly, A. D. (1993b). Teratogenic effects of selenium in natural populations of freshwater fish. *Ecotoxicol. Environ. Saf.* **26**, 181–204.
- Lemly, A. D. (1995). A protocol for aquatic hazard assessment of selenium. *Ecotoxicol. Environ. Saf.* **32**, 280–288.
- Lemly, A. D. (1996). Assessing the toxic threat of selenium to fish and aquatic birds. *Environ. Monitor. Assess.* **43**, 19–35.
- Lemly, A. D. (1997a). Environmental implications of excessive selenium. *Biomed. Environ. Sci.* **10**, 415–435.
- Lemly, A. D. (1997b). A teratogenic deformity index for evaluating impacts of selenium on fish populations. *Ecotoxicol. Environ. Saf.* **37**, 259–266.
- Lemly, A. D., Finger, S. E., and Nelson, M. K. (1993). Sources and impacts of irrigation drainwater contaminants in arid wetlands. *Environ. Toxicol. Chem.* **12**, 2265–2279.
- Margolin, S. (1979). Liability under the Migratory Bird Treaty Act. *Ecol. Law Q.* **7**, 989–1010.
- Marshall, E. (1985). Selenium poisons refuge, California politics. *Science* **229**, 144–146.
- Moore, S. B., Winckel, J., Detwiler, S. J., Klasing, S. A., Gaul, P. A., Kanim, A. R., Kesser, B. E., DeBevec, A. B., Beardsley, A., and Puckett, L. K. (1990). *Fish and Wildlife Resources and Agricultural Drainage in the San Joaquin Valley, California*. San Joaquin Valley Drainage Program, Sacramento, CA.
- Moshiri, G. A. (1993). *Constructed Wetlands for Water Quality Improvement*. Lewis, Boca Raton, FL.
- National Irrigation Water Quality Program (NIWQP) (1998). Guidelines for interpretation of the biological effects of selected, constituents in biota, water, and sediment, *Information Rep. No. 3*. U.S. Department of the Interior, National Irrigation Water Quality Program, Denver, CO.
- Ohlendorf, H. M. (1989). Bioaccumulation and effects of selenium in wildlife. *Soil Sci. Soc. Am. Spec. Pub.* **23**, 133–177.
- Ohlendorf, H. M., Hoffman, D. J., Saiki, M. K., and Aldrich, T. W. (1986a). Embryonic mortality and abnormalities of aquatic birds: Apparent impacts of selenium from irrigation drainwater. *Sci. Total Environ.* **52**, 49–63.
- Ohlendorf, H. M., Hothem, R. L., Bunck, C. M., Aldrich, T. W., and Moore, J. F. (1986b). Relationships between selenium concentrations and avian reproduction. *Trans. North Am. Wildl. Nat. Res. Conf.* **51**, 330–342.
- Ohlendorf, H. M., Kilness, A. W., Simmons, J. L., Stroud, R. K., Hoffman, D. J., and Moore, J. F. (1988a). Selenium toxicosis in wild aquatic birds. *J. Toxicol. Environ. Health* **24**, 67–92.
- Ohlendorf, H. M., Hothem, R. L., and Aldrich, T. W. (1988b). Bioaccumulation of selenium by snakes and frogs in the San Joaquin Valley, California. *Copeia* **1988**, 704–710.
- Ohlendorf, H. M., Hothem, R. L., and Welsh, D. (1989). Nest success, cause-specific nest failure, and hatchability of aquatic birds at selenium-contaminated Kesterson Reservoir and a reference site. *Condor* **91**, 787–796.
- Ohlendorf, H. M., Hothem, R. L., Bunck, C. M., and Marois, K. C. (1990). Bioaccumulation of selenium in birds at Kesterson Reservoir, California. *Arch. Environ. Contam. Toxicol.* **19**, 495–507.
- Parker, M., and Knight, A. W. (1989). *Biological Characterization of Agricultural Drainage Evaporation Ponds, Water Science and Engineering Paper 4521*. Department of Land, Air, and Water Resources, Univ. of California, Davis.
- Popkin, R. (1986). Kesterson: Nonpoint nightmare. *EPA J.* **12**, 13–14.
- Rodgers, J. H., Jr., and Dunn, A. W. (1992). Developing design guidelines for constructed wetlands to remove pesticides from agricultural runoff. *Ecol. Eng.* **1**, 83–95.
- Saiki, M. K. (1986a). A field example of selenium contamination in an aquatic food chain. In *Irrigation Drainage and California Agriculture*, California Agriculture Technology Pub. CAT1/860201, pp. 67–76. CAT Institute, Fresno, CA.
- Saiki, M. K. (1986b). Concentrations of selenium in aquatic food-chain organisms and fish exposed to agricultural tile drainage water. In *Selenium and Agricultural Drainage: Implications for San Francisco Bay and the California Environment—Selenium II* (A. Q. Howard, Ed.), pp. 25–33. Bay Institute of San Francisco, Tiburon, CA.
- Saiki, M. K., and Ogle, R. S. (1995). Evidence of impaired reproduction by western mosquitofish inhabiting seleniferous agricultural drainwater. *Trans. Am. Fish. Soc.* **124**, 578–587.
- Saiki, M. K., Jennings, M. R., and Hamilton, S. J. (1991). Preliminary assessment of the effects of selenium in agricultural drainage on fish in the San Joaquin Valley. In *The Economics and Management of Water and Drainage in Agriculture* (A. Dinar and D. Zilberman, Eds.), pp. 369–385. Kluwer Academic, Boston.
- San Joaquin Valley Drainage Program (SJVDP) (1988). *Status Report 10*. SJVDP, Sacramento, CA.
- San Joaquin Valley Drainage Program (SJVDP) (1990). *Status Report 17*. SJVDP, Sacramento, CA.
- San Joaquin Valley Interagency Drainage Program (SJVDP) (1979). *Agricultural Drainage and Salt Management in the San Joaquin Valley: Final Report*. SJVIDP, Fresno, CA.
- Schuler, C. A., Anthony, R. G., and Ohlendorf, H. M. (1990). Selenium in wetlands and waterfowl foods at Kesterson Reservoir, California. *Arch. Environ. Contam. Toxicol.* **19**, 845–853.
- Skorupa, J. P. (1998). Selenium poisoning of fish and wildlife in nature: Lessons from twelve real-world experiences. In *Environmental Chem-*

- istry of Selenium (W. T. Frankenberger, Jr., and R. A. Engberg, Eds.), pp. 315–354. Marcel Dekker, New York.
- Skorupa, J. P., and Ohlendorf, H. M. (1991). Contaminants in drainage water and avian risk thresholds. In *The Economics and Management of Water and Drainage in Agriculture* (A. Dinar and D. Zilberman, Eds.), pp. 345–368. Kluwer Academic, Boston.
- Skorupa, J. P., Morman, S. P., and Sefchick-Edwards, J. S. (1996). Guidelines for Interpreting Selenium Exposures of Biota Associated With Nonmarine Aquatic Habitats. *Tecnn. Rep.* U.S. Fish and Wildlife Service, Sacramento Field Office, Sacramento, CA.
- Sorensen, E. M. B. (1986). The effects of selenium on freshwater teleosts. *Rev. Environ. Toxicol.* **2**, 59–116.
- Terry, N., and Zayed, A. (1998). Phytoremediation of selenium. In *Environmental Chemistry of Selenium* (W. T. Frankenberger, Jr., and R. A. Engberg, Eds.), pp. 633–655. Marcel Dekker, New York.
- U.S. Environmental Protection Agency (USEPA) (1992). *Framework for Ecological Risk Assessment*, EPA/630/R-92/001. USEPA, Office of Water, Washington, DC.
- U.S. Environmental Protection Agency (USEPA) (1998). *Guidelines for Ecological Risk Assessment*, EPA/630/R-95/002F. USEPA Risk Assessment Forum, Washington, DC.
- U. S. Fish and Wildlife Service. (1998). *Endangered Species Bulletin*, Vol. 23, No. 1 (January-February). U.S. Department of the Interior, Washington, DC.
- U.S. General Accounting Office (USGAO) (1987). *National Refuge Contamination Is Difficult To Confirm And Clean Up*. Publi. GAO/RCED-87-128. USGAO, Washington, DC.
- Vencil, B. (1986). The Migratory Bird Treaty Act—Protecting wildlife on our national refuges—California's Kesterson Reservoir, a case in point. *Natural Resour. J.* **26**, 609–627.
- Williams, M., Hothem, R. L., and Ohlendorf, H. M. (1989). Recruitment failure in American avocets and black-necked stilts nesting at Kesterson Reservoir, California, 1984–1985. *Condor* **91**, 797–802.
- Zahm, G. R. (1986). Kesterson Reservoir and Kesterson National Wildlife Refuge: History, current problems, and management alternatives. *Trans. North Am. Wildl. Nat. Res. Conf.* **51**, 324–329.